

## Development and Testing of Space Fission Technology at NASA-MSFC

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### ABSTRACT:

The Early Flight Fission – Test Facility (EFF-TF) at NASA-Marshall Space Flight Center (MSFC) provides a capability to perform hardware-directed activities to support multiple in-space nuclear reactor concepts by using a non-nuclear test methodology [1,2]. This includes fabrication and testing at both the module/component level and near prototypic reactor configurations allowing for realistic thermal-hydraulic evaluations of systems. The EFF-TF is currently performing non-nuclear testing of hardware to support a technology development effort related to an affordable fission surface power (AFSP) system that could be deployed on the Lunar surface [3]. The AFSP system is presently based on a pumped liquid metal-cooled reactor design [4,5], which builds on US and Russian space reactor technology as well as extensive US and international terrestrial liquid metal reactor experience. An important aspect of the current hardware development effort is the information and insight that can be gained from experiments performed in a relevant environment using realistic materials. This testing can often deliver valuable data and insights with a confidence that is not otherwise available or attainable.

While the project is currently focused on potential fission surface power for the lunar surface, many of the present advances, testing capabilities, and lessons learned can be applied to the future development of a low-cost in-space fission power system. The potential development of such systems would be useful in fulfilling the power requirements for certain electric propulsion systems (magnetoplasmadynamic thruster, high-power Hall and ion thrusters). In addition, in-space fission power could be applied towards meeting spacecraft and propulsion needs on missions further from the Sun, where the usefulness of solar power is diminished. The affordable nature of the fission surface power system that NASA may decide to develop in the future might make derived systems generally attractive for powering spacecraft and propulsion systems in space.

This presentation will discuss work on space nuclear systems that has been performed at MSFC's EFF-TF over the past 10 years. Emphasis will be placed on both ongoing work related to FSP and historical work related to in-space systems potentially useful for powering electric propulsion systems.

### REFERENCES

- [1] T. J. Godfroy, M. Van Dyke, and R. Dickens, "Realistic Development and Testing of Fission Systems at a Non-Nuclear Testing Facility," Space Technologies and Applications International Forum (STAIF-2000), *AIP Conf. Proc.*, **504**:1208 (2000).
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- [3] M. Houts, S. Gaddis, R. Porter et al., "Options for Affordable Fission Surface Power Systems," Proceedings of the 2006 International Congress on Advances in Power Plants (ICAPP), ANS, paper 6370 (2006).

- [4] D. D. Dixon, M. Hiatt, D. I. Poston et al., "Design of a 25-kWe Surface Reactor System Based on SNAP Reactor Technologies," Space Technology and Applications International Forum (STAIF-2006), *AIP Conf. Proc.*, **813**:932 (2006).
- [5] D. I. Poston, R. J. Kapernick, D. D. Dixon et al., "Reference Reactor Module for the Affordable Fission Surface Power System," Space Technology and Applications International Forum (STAIF-2008), *AIP Conf. Proc.*, **969**:277 (2008).



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44<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference

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# Nuclear Surface Power Systems

## ◆ Power anytime, anywhere on Moon or Mars

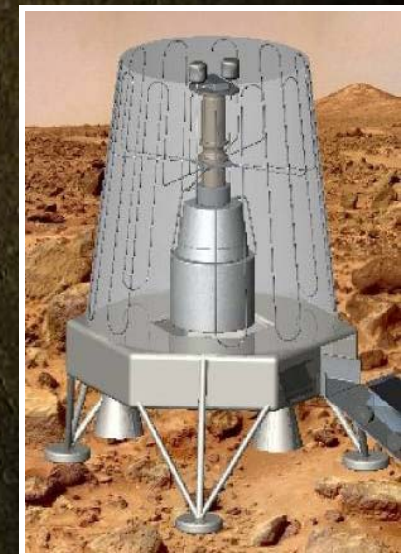
- Operate through lunar night
- Operate in permanently shaded regions
- Operate through Mars global dust storms
- Operate at high Martian latitudes

## ◆ Enable power-rich architecture

- Site Preparation, In-Situ Resource Utilization, Propellant Production, Fabrication, Life support, Communication, Mobility, Deep Drilling

## ◆ Nuclear technology useful anywhere in space

- Not dependent on available sunlight

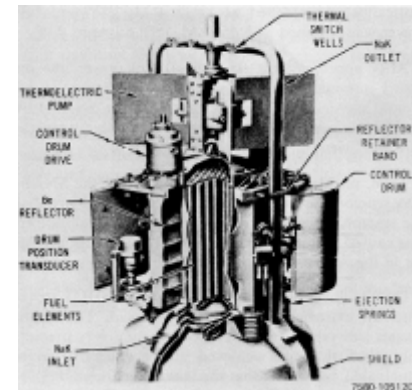




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# Space Power Reactors – Historical Perspective

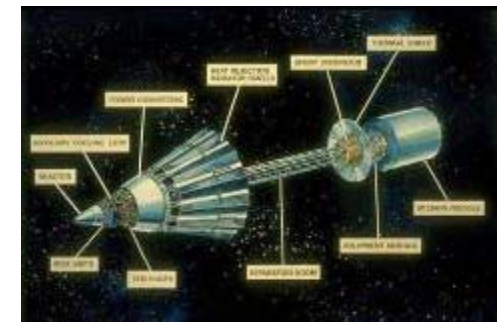
- ◆ SNAP reactors (1960s to early 1970s)
  - UZrH fueled, liquid metal (NaK) cooled w/thermoelectrics or Rankine
  - 500 W<sub>e</sub> to 60 kW<sub>e</sub> (1 year life)
  - Several ground tests
  - One (SNAP-10A) flown in Earth orbit
- ◆ Russian reactors
  - U-Mo Alloy or UO<sub>2</sub> fueled, liquid metal (NaK) cooled w/thermoelectrics (>30) or thermionics (2)
  - Low power (3-5 kW<sub>e</sub> / 100-150 kW<sub>t</sub>), short life (≤ 1 year)
  - Over 30 reactors flown in Earth orbit
- ◆ Numerous other programs developed technology but didn't lead to flight



0.5 kW<sub>e</sub> SNAP-10A Thermoelectric



5 kW<sub>e</sub> TOPAZ  
Thermionic



Artist Conception of SP100





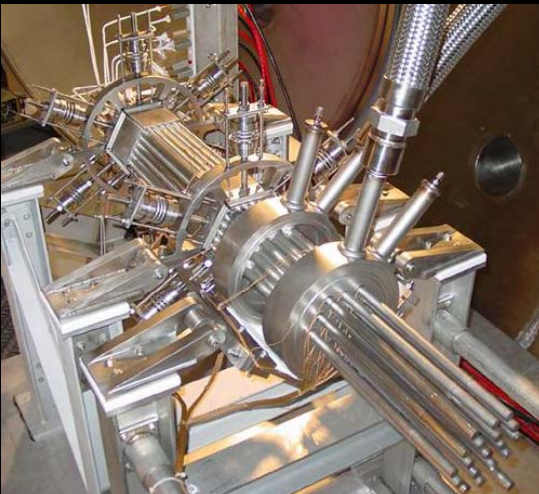
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# Recent Efforts at NASA-MSFC

- ◆ Hardware-directed non-nuclear test methodology
  - Testing at module/component level and near prototypic reactor configurations
  - Realistic thermal/hydraulic testing of a reactor design using resistive heater elements that accurately simulate reactor response

## SAFE 100A Simulated Heat Pipe Reactor

- 100 kW<sub>t</sub> design
- 19 heat pipe modules
- 54 heater elements
- Gas flow heat exchanger mounted to heat pipe condensers

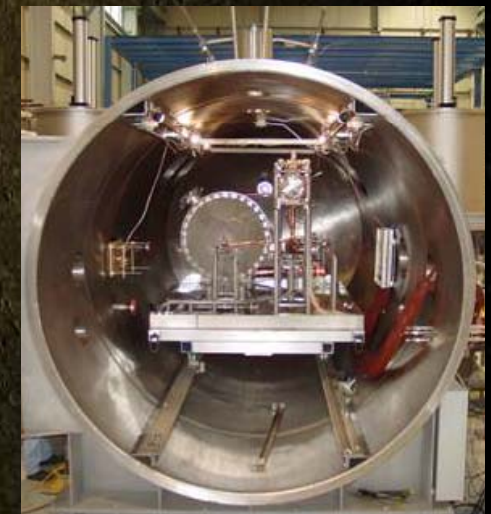


## Direct Drive Gas (DDG) Reactor

- Simulated compact fast spectrum reactor
- 37 fuel pin core assembly with power levels up to 100 kW<sub>t</sub>

## Pumped NaK Simulated Reactor

- 37 fuel pin core assembly with power levels up to 44 kW<sub>t</sub>
- Electromagnetic NaK pump
- Test section for component testing







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# Planetary Surface Missions: Growing Energy Needs



## ◆ Now:

- 290 W<sub>e</sub> Deep Space / 110 W<sub>e</sub> Multi-Mission RTG (MMRTG)
- General Purpose Heat Source - Radioisotope Thermoelectric Generator (GPHS-RTG) uses 18 Pu-238 fueled GPHS modules
- GPHS modules will be used by the 110 W<sub>e</sub> MMRTG (8 modules) and the 110 W<sub>e</sub> Stirling Radioisotope Generator (SRG, 2 modules)

**MMRTG selected for  
Mars Science Laboratory**

## ◆ Affordable Option for ~2020

- 40 kW<sub>e</sub> modular Fission Surface Power System (FSPS) with ~8 yr life
- 25 to 80+ kW<sub>e</sub> power levels with part power or 2<sup>nd</sup>/additional FSPS
- Well established reactor technology – minimize new technology development
- Compact, robust, safe design with ample margins for up to 2 units/lander
- Provides power-rich environment anytime / anywhere
- Not affected by Pu-238 availability concerns



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# **“Affordable” Approach**

**Fission Surface Power (FSP) must be ‘affordable’ and ‘safe’ relative to other options**

- ◆ **Select low temperature, stainless steel, liquid metal reactor system with substantial terrestrial data and experience**
- ◆ **Employ “Affordable” Design Philosophy**
  - Also, ensure early-on that design is extensible to Mars surface
- ◆ **Extensive use of non-nuclear testing**
  - Detailed component development and testing
  - Integrated system testing
- ◆ **Judicious use of nuclear testing**
  - Cold critical experiments (early designs)
  - Hot critical experiments (mature designs)
  - Reactor irradiations
  - Acceptance check of flight unit
  - Start-up operations on the Moon
- ◆ **Minimize construction of new facilities**





# **“Affordable” Design Philosophy**

## ◆ **Conservative**

- Low Temperature
- Known Materials and Fluids
- Generous Margins
- Large Safety Factors
- Terrestrial Design Basis

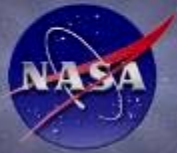
## ◆ **Simple**

- Modest Power & Life Requirements
- Simple Controls
  - Negative Temperature Reactivity Feedback: assures safe response to reactor temperature excursions
  - Parasitic Load Control: maintains constant power draw regardless of electrical loads and allows thermal system to remain near steady-state
- Slow Thermal Response
- Conventional Design Practices
- Established Manufacturing Methods
- Modular and Testable Configurations

## ◆ **Robust**

- High Redundancy
- Fault Tolerance... including ability to recover from severe conditions such as:
  - Loss of Reactor Cooling
  - Stuck Reflector Drums
  - Power Conversion Unit Failure
  - Radiator Pump Failure
  - Loss of Radiator Coolant
  - Loss of Electrical Load
- High TRL Components
- Hardware-Rich Test Program
- Multiple Design Cycles

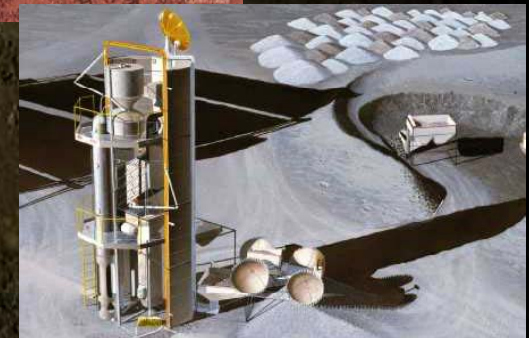
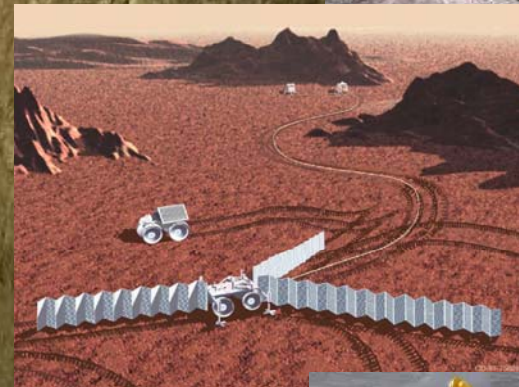
**Minimize Cost by  
Reducing Risk --  
Accept Mass Penalties  
if Needed**



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# FSP Features & Benefits

- ◆ **Continuous Day/Night Power for Robust Surface Ops**
- ◆ **Same Technology for Moon and Mars**
- ◆ **Suitable for any Surface Location**
  - Lunar Equatorial or Polar Sites
  - Permanently Shaded Craters
  - Mars Equatorial or High Latitudes
- ◆ **Environmentally Robust**
  - Lunar Day/Night Thermal Transients
  - Mars Dust Storms
- ◆ **Operationally Robust**
  - Multiple-Failure Tolerant
  - Long Life without Maintenance
- ◆ **Highly Flexible Configurations**
  - Excavation Shield Permits Near-Habitat Siting
  - Option for Above-Grade System or Mobile System (with shield mass penalty)
  - Option for Remote Siting (with high voltage transmission)
  - Option for Process Heat Source (for ISRU or habitat)







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## FSP Features & Benefits (cont.)

### ◆ Safe During All Mission Phases

- Launched Cold, No External Radiation Hazard Until Startup
- Safe during Operation with Excavation or Landed Shield
- Safe after Shutdown with Negligible Residual Radiation

### ◆ Scalable to Higher Power Levels

### ◆ Performance Advantages Compared PV/RFC

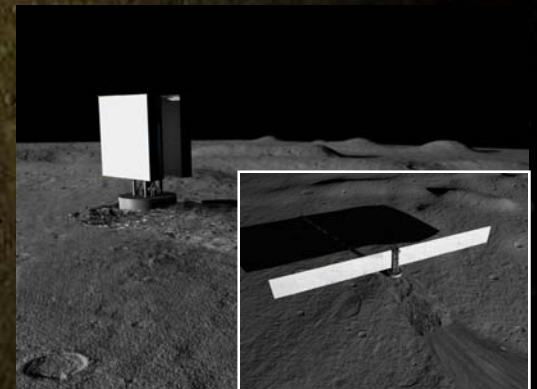
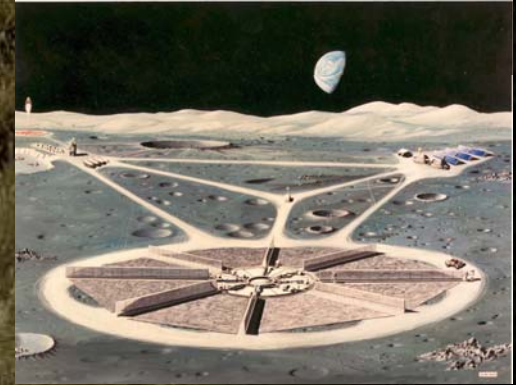
- Significant Mass & Volume Savings for Moon
- Significant Mass & Deployed Area Savings for Mars

### ◆ Competitive Cost with PV/RFC

- Detailed, 12-month “Affordable” Fission Surface Power System Cost Study Performed by NASA & DOE
- \$1.4B to First Flight Unit, ~\$215M per additional unit
- Modest Unit Cost Enables Multiple Units and/or Multiple Sites

### ◆ Technology Primed for Development

- Terrestrial Reactor Design Basis
- No Material Breakthroughs Required
- Lineage to RPS Systems (e.g. Stirling) and ISS (e.g. Radiators, Electrical Power Distribution)

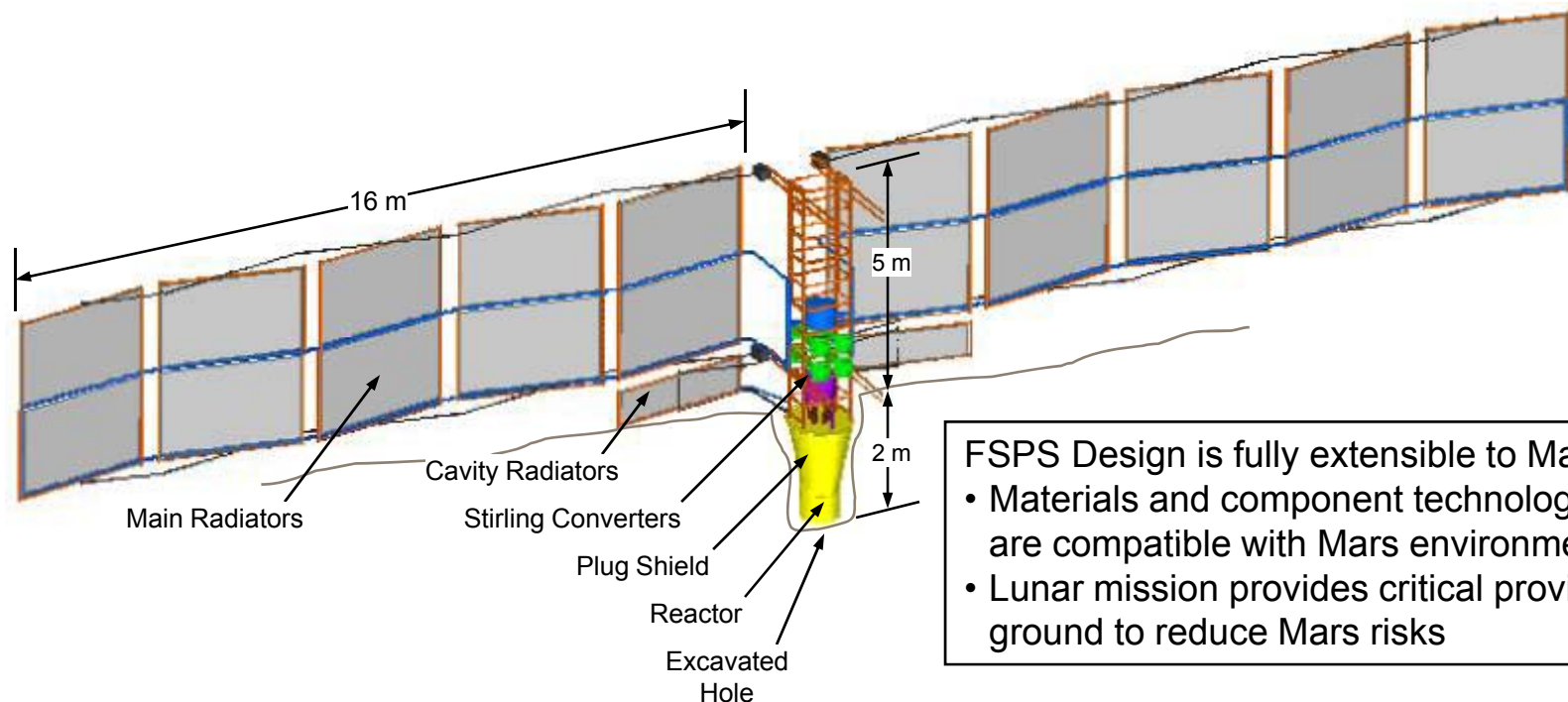




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# Affordable Fission Surface Power System (FSPS)

- ♦ Modular 40 kWe System with 8-Year Design Life suitable for (Global) Lunar and Mars Surface Applications
- ♦ Emplaced Configuration with Regolith Shielding Augmentation Permits Near-Outpost Siting
  - <5 rem/yr at 100 m Separation
- ♦ Low Temperature, Low Development Risk, Liquid-Metal (NaK) Cooled Reactor with  $\text{UO}_2$  Fuel and Stainless Steel Construction



FSPS Design is fully extensible to Mars:

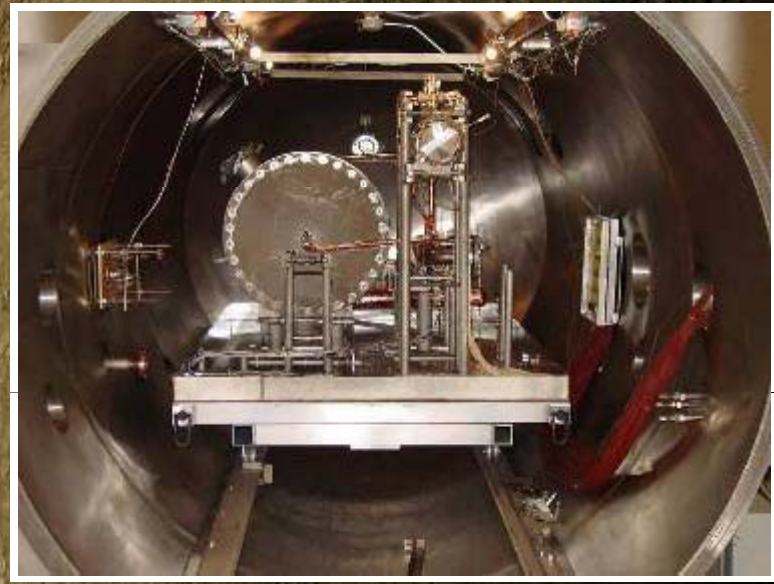
- Materials and component technologies are compatible with Mars environment
- Lunar mission provides critical proving ground to reduce Mars risks





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# Fission Surface Power Primary Test Circuit (FSP-PTC) at NASA-MSFC



- ◆ Pumped NaK reactor simulator loop
- ◆ Test section to allow integration of NASA-GRC Stirling-cycle generator
- ◆ Preparation for design/development/testing of full Technology Demonstration Unit (TDU)
  - Prototypic FSPS reactor simulator
  - Power generation
  - PCAD
  - Radiators



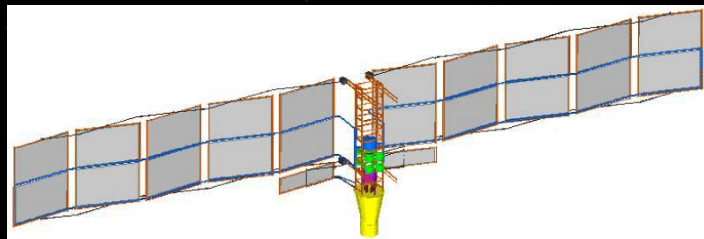


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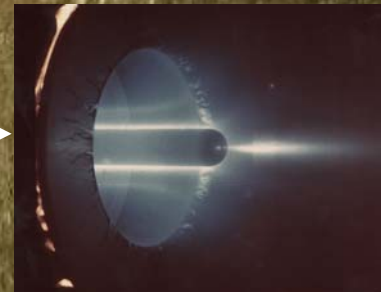
# Extension to In-Space Power Generation

- ◆ FSPS technology closely-related to in-space pumped-NaK reactors
- ◆ Design and lessons-learned from FSPS development applicable to a new generation of in-space fission power systems
- ◆ Potentially useful for missions requiring high-power electric propulsion systems
- ◆ Potentially beneficial for power and propulsion requirements on missions further from the Sun

FSPS based in-space system



Propulsion systems

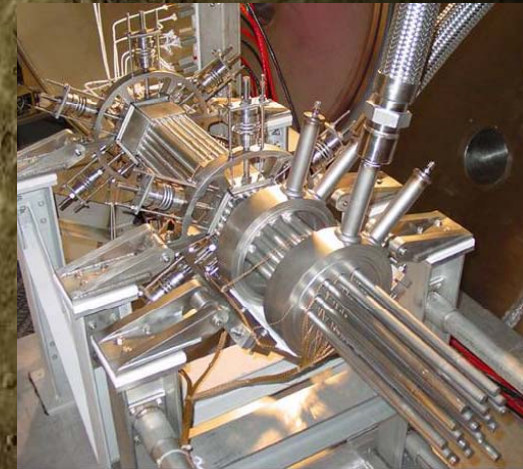






# Recent NASA-MSFC In-Space Power Generation Efforts

- ◆ SAFE-30 reactor simulator end-to-end demo at NASA-JPL (2001-2002)
  - 30 kW<sub>t</sub> heat pipe reactor simulator
  - 350 W<sub>e</sub> Stirling-cycle power conversion
  - Power provided for operation of an NSTAR ion thruster



- ◆ Gas-core reactor simulator efforts
  - JIMO/Prometheus development
  - DDG reactor simulator
  - Brayton-cycle gas-generator power conversion
  - JIMO requirement for several hundred kW<sub>e</sub> power generation
- Presently testing 100 kW<sub>t</sub> DDG coupled with NASA-GRC developed Brayton-cycle generator at NASA-GRC for potential FSP applications



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# Acknowledgements

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- ◆ Any opinions expressed in this presentation are those of the authors and do not necessarily reflect the position of NASA